DISPERSION OF EFFLUENT PLUMES FROM DIFFUSERS ON NEAR-SHORE REGIONS OF THE GREAT LAKES

VOLUME II

SURFACE DILUTION

AN ASSESSMENT PROCEDURE

PREPARED FOR

WORKING GROUP II
OF THE WATER MANAGEMENT
STEERING COMMITTEE

Ontario
Environment
Environnement

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Great Lakes Section
Water Resources Branch
August, 1981

NOTE

The receiving water assessment techniques presented in this report describe the methods commonly in use within the Ministry. Alternative techniques exist and/or will eventually be developed. Consultation with Ministry of the Environment staff is advisable to determine the suitability of the alternative techniques.

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DISPERSION OF EFFLUENT PLUMES
FROM DIFFUSERS ON NEAR-SHORE REGIONS OF THE GREAT LAKES
(SURFACE DILUTION)

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DISPERSION OF EFFLUENT PLUMES FROM DIFFUSERS ON NEAR-SHORE REGIONS OF THE GREAT LAKES

(SURFACE DILUTIONS)

SUMMARY

A two-dimensional analytical model to predict surface dilutions from a diffuser outfall, in a steady current regime, is discussed. Simple graphical and analytical solutions are presented along with a fully worked out example. For most cases, graphical solutions are recommended for simplicity to obtain dilution ratios at any required distance from the source or diffuser. Analytical solutions may be used when the results are beyond the range of the graphical solutions.

DISPERSION OF EFFLUENT PLUMES
FROM DIFFUSERS ON NEAR-SHORE REGIONS OF THE GREAT LAKES
(SURFACE DILUTION)

INTRODUCTION

After the waste has been initially diluted (Hamdy, 1981) by the jet rise, the effluent field begins to drift with the prevailing currents and spreads on the lake surface in the shape of a plume by entraining freshwater at the plume edges. This is referred to as surface dilution.

Currents

The lake currents are generally variable with the time (see example for Lake Ontario, Figure 1). Generally, the lake is considered stagnant if the current speed is less than 5 cm/s. Occassionally, the current speeds can be as high or higher than 30 cm/s due to the coastal jetting. It is important to use the appropriate value of current speed in any prediction model. If the water movement data, in the region of concern, are not available. current speeds and directions should be measured by drogues under different wind conditions.

The variability of the currents (see Figure 1) in magnitude and direction are responsible for the dispersion and dilution of a pollutant. In steady state disperion models, an average speed is generally used. Variable currents are utilized in more complex time- variant models, such as hydrodynamic and stochastic models. A computer model (Kuehnel et al, 1981), using the variable currents or the time series of current speed and direction over a period, is presently being tested. As this model will use the current meter data (Figure 1) and not just an average current speed, it is expected to yield more reliable results. However, its use will be limited to the sites where current meters have been operated for extended periods.

Surface Plume

Figures 2 and 3 depict the behaviour of typical plumes from a multiport diffuser. Due to the jet rise, the plume from each port will travel a horizontal distance x_1, from the diffuser centreline and have individual plume widths w and centreline dilutions D_1 at the surface (see Figures 2 and 3). Computation of x_1, w and D_1, in the nearfield, have been discussed by Hamdy (1981).

The sewage field is then further diluted due to one or all of the following processes:

(a) Midfield dilution (D_2) of individual surface plumes, from each diffuser port before they merge into one another (see Figure 2).

(b) Farfield dilution (D_3) of the already merged plume (see Figures 2 and 3).

(c) Apparent dilution (D_4) applies to the decay of non-conservative pollutants, such as coliforms and chlorine at all points in the plume.

Dilutions D_1, and D_2 and D_3 of a conservative pollutant maintains the total mass of the pollutant but reduces the concentration of the pollutant. However, D_4 reduces the mass of the non-conservative pollutant due to the decay or bio-chemical reactions; thereby reducing the concentration of such pollutant.

DILUTIONS

Various centreline dilutions are defined as follows; the proper use of symbols is illustrated in Figures 2 and 3.

$$\text{Nearfield Dilution, } D_1 = \frac{C_1}{C_0} \qquad (1)$$

where C_0 = effluent concentration of pollutant at the exit of the diffuser

C_1 = plume centreline concentration of the pollutant at the surface, at the interface NN (i.e. interface of nearfield and midfield, Figure 2).

$$\text{Midfield Dilution, } D_2 = \frac{C_2}{C_1} \qquad (2)$$

where C_2 = plume centreline concentration of the pollutant at the interface FF of midfield and far-field (Figure 2 and 3).

$$\text{Farfield Dilution, } D_3 = \frac{C_3}{C_2} \qquad (3)$$

where C_3 = plume centreline concentration of the pollutant in the farfield at a distance x_3 from the interface FF between mid-field and far-field.

D_4 = apparent dilution due to decay of non-conservative pollutants. This will be discussed, in more detail, in a subsequent section.

$$\text{Total Dilution, } D_x = D_1 \cdot D_2 \cdot D_3 \cdot D_4 \qquad (4)$$

$$\text{at } x = x_1 + x_2 + x_3 \text{ (see figure 2)} \qquad (5)$$

When there is no midfield dilution:

$x_2 = 0$
$D_2 = 1.0$
$C_2 = C_1$

The midfield plume will develop only if $w < \ell$ where ℓ = port spacing and w, the width of each plume. When the plume width has grown from w to ℓ (see Figure 2), the midfield region ends and the farfield region begins.

If $w < \ell$, there will be no midfield region (see Figure 3) as the individual jet plumes would have merged before reaching the lake surface.

Since the surface plume advection and dispersion, in the midfield and farfield region, are governed by the prevailing currents and the width of the initial sewage field, one model would be applicable to both regions. The width of the initial sewage field is w for the midfield and the diffuser length (b) for the farfield.

Modelling

Several one-dimensional and two dimensional models for predicting the dilution of pollutant concentration of the waste plume have been developed. Foxworthy et al (1966) developed a statistical model requiring field measurements. Brooks (1960) approached the problem analytically to solve the classical partial differential equations. From the several models available, the one developed by Brooks (1960) has been chosen for this manuscript for its simplicity and reliability. The only measured or estimated input required, for this model, is the average current speed. The model is briefly described below.

Brooks Model

The following are the main assumptions of this model.

(a) Eddy diffusivity (E) is a variable, and is a function of the initial plume width (p) or the diffuser length (b).

(b) Longitudual mixing (along the direction of current) and the vertical mixing is negligible.

(c) steady flow of discharge from the outfall.

In general, dilution D, due to the initial plume width (p) and at a distance x, from virtual source can be estimated by Brooks model.

$$D = \operatorname{erf}\sqrt{1.5/\left[\left\{(1 + 0.67\ \beta(x/p)\right\}^{3} - 1\right]} \quad (6)$$

where p = initial plume width

$\beta = 8E/Up$ (7)

$E = 0.01\ p^{1.33}$ in cgs units (8)

= Eddy Diffusivity

U = mean speed of prevailing currents

The sewage width (L) can be computed as:

$$L/p = \left[1 + 0.67\ \beta\left(\frac{x}{p}\right)\right]^{1.5} \quad (9)$$

The dilutions as computed above are for the centreline of the plume, in x directions (y = 0). Thus, $D_{(x,\ o)}$ = D (already computed) If dilutions at any point (x, y) in the plume is required, it can be computed as:

$$D_{(x,\ y)} = D_{(x,\ o)} \cdot D_5 \quad (10)$$

where $D_5 = \exp\left[-18\,(y/L)^{2}\right]$ (11)

Symbols x,y, b and L are illustrated in Figures 2 and 3.

As analytical solutions of equations (6), (9) and (10) may not be convenient for some users, the respective monographs are presented in Figures 4, 5 and 6. Dilutions and plume width at any distance can be obtained from graphs by first computing $\beta(x/p)$ and for the two-dimensional dilution, $\left[18\,(y/L)^{2}\right]$ will have to be computed.

Equation (6) can always be solved with the help of Table 1 (see Sample Collections).

Midfield Dilution (D_2)

If $w < \ell$, the midfield region will develop. The length of the midfield region x_2 (see Figure 2) can be computed as:

$$x_2 = \left[12.5\ U\ w^2/\ell^{1.33}\right]\left[(\ell/w)^{0.67} - 1\right] \qquad (12)$$

where ℓ = port spacing

It is very important to keep all variables of (12) in cgs units (i.e. cm and sec) and obtain x_2 in cm. x_2 can then be converted to any other units, if desired.

For the midfield dilution D_2; x_2 should be used in equations (6) and (10) instead of x; and w instead of p in equations (6) to (10). Note that equation (9) may not be required for the midfield region because

$$\text{Max } (L) = \ell = \text{port spacing}$$

Intermediate values of plume width in the midfield region are not of any significant use. If necessary, the width of the plumes before merging may be computed by (9) using the appropriate x and p values.

Farfield Dilution (D_3)

The intial plume width of the farfield is generally equal to the diffuser length (b). Equations (6), (7), (8), (9), (10) and (11) may be applied to the farfield region by replacing

x by x_3
p by b
D by D_3

Decay Dilution (D_4)

The concentration of non-conservative pollutants are reduced by decay of their mass (by biochemical reaction, mortality of indicator bacteria, etc.). Such decay from all causes except dispersion, may be expressed by the first order equation:

$$D_4 = \exp(-kt) \tag{13}$$

where k = first-order decay rate to be determined experimentally or may be obained from literature. Note that equation (13) is applicable to non-conservative pollutants (e.g. Chlorine, ammonia, phenol and indicator bacteria, etc.) whose decay may be approximated by the first-order kinetics.

$t = \frac{x}{u}$ = time of travel

Values of k should be determined from field studies where possible; some typical values obtained from our unpublished studies are:

for coliform, $k = 16 \times 10^{-5}/s$

for chlorine, $k = 20 \times 10^{-5}/s$ in summer

$= 6 \times 10^{-5}/s$ in winter

for a conservative pollutant, $k = 0$, and therefore $D_4 = 1.0$

SAMPLE CALCULATIONS

Lakeview Diffuser Outfall

A. Present case; Effluent discharge rate, $Q_1 = 1.96\ m^3/s$.

Hamdy (1981) have computed the following for the above example.

$\ell = 12$ m
$w = 4.4$ m
$x_1 = 12$ m
$D_1 = 0.077$

Since $w < \ell$, there is no interference of individual jets. Figure 2 depicts the behaviour of such sewage field. Thus, there will be midfield spreading resulting in dilution D_2.

Consider the case with a mean current speed, $U = 10$ cm/s.

(a) Midfield Dilution D_2

Using equation (12), we compute x_2 :

Remember that all variables must be in cgs (cm and s) units for this equation; therefore,

$$x_2 = \frac{12.5(10)(440)^2}{(1200)^{1.33}} \left[\left(\frac{1200}{440}\right)^{0.67} - 1\right]$$

$$= 1898(0.95) = 1807 \text{ cm}$$

$$= 18.07 \text{ m}$$

Since we need to determine dilution D_2 at $x_2 = 18$ m for a sewage width of 4.4 m, the use of nomograph is not recommended because

$$\beta(x/b) \text{ or } \beta(x_2/w) \text{ is less than } 1.0$$

Using the more accurate analysis of equations (6), (7), and (8) as follows:

From (8):

$$E = 0.01(440)^{1.33} = 33.5 \text{ cm}^2/\text{s}$$

From (7):

$$\beta = 8E/Uw = \frac{8 \times 33.5}{10 \times 440} = 0.061$$

$$x_2 = 1800 \text{ cm}$$

From (6):

$$D_2 = \mathrm{erf}\sqrt{\left[1.5/\ \left\{1 + 0.67(0.061)\left(\frac{1800}{400}\right)\right\}^3 - 1\right]}$$

$$= \mathrm{erf}\ \sqrt{1.5/(1.59 - 1)}$$

$$= \mathrm{erf}\sqrt{(2.5)} \quad = \quad \mathrm{erf}\ (1.58)$$

$$= 0.9996 \text{ from Table 1}$$

(b) Farfield Dilution D_3

b = 210 m 690 ft (Hamdy, 1981)
U = 10 cm/s 20 fpm (assumed)

Assume that the dilution D_3 is required at $X_3 = 2100$m.

From (8):

$$E = 0.1\ (21000)^{1.33} = 5792\ \mathrm{cm^2/s}$$

From (7):

$$\beta = \frac{8E}{ub} = \frac{8 \times 5792}{10 \times 21000} = 0.22$$

For $x = 2100$ m, $\beta\left(\frac{x}{b}\right) = 0.22\left(\frac{2100}{210}\right)$

$$= 2.2$$

Using Figure 4 and $\beta\left(\frac{x}{b}\right) = 2.2$, Dilution can be read as:

$$D_3 = 0.38$$

The plume width (L) at $x_3 = 2100$m can be obtained by using Figure 5.

For $\beta\left(\frac{x}{b}\right) = 2.2$, $\frac{L}{b} = 4.0$

$$L = 4b = 4 \times 210$$

$$L = 840 \text{ m}$$

(c) 2-dimensional dilution

Dilution at a point whose co-ordinates are (x, y) i.e. not on centreline

Let $x = 2100$ m and $y = 210$ m

$$D_3(x, y) = D_3(x, o) \cdot D_5$$

For D_5, compute $18\,(Y/L)^2 = 18\left(\frac{210}{840}\right)^2 = 1.1$

From figure 6, $D_5 = 0.33$

$$D_3(2100, 210) = 0.38 \times 0.33$$
$$= 0.125$$

Similarly, dilution at any point within the plume (i.e. at a distance y from the plume centreline) can be computed.

(d) Total Dilution at Plume Centreline,

at $x_3 = 2100$ m for conservative pollutant, $D_4 = 1.0$

$$D_x = D_1 \cdot D_2 \cdot D_3 \cdot D_4$$

$$= (0.077)(0.976)(0.38)(1.0)$$
$$= 0.0286$$

where $x = x_1 + x_2 + x_3$
$= 12 + 18 + 2100$
$= 2130$ m

Thus the total dilution of a conservative pollutant at 2130 m from the diffuser is:

$$D_{2130} = 0.0286$$

(e) Decay Dilution (D_4)

Now consider a non-conservative pollutant, e.g. coliforms decay rate for coliforms, $k = 16 \times 10^{-5}/s$

$$t = \frac{x}{u} = \frac{21300}{10} = 21300 \text{ s}$$

therefore

$$kt = 16 \times 10^{-5} \times 21300$$
$$= 3.408$$

From (13):

$$D_4 = \exp(-3.408) = 0.033$$

For coliform, $D_{870} = D_1 \cdot D_2 \cdot D_3 \cdot D_4$

$$= (0.077)(0.976)(0.38)(0.033)$$

$$= 0.00094$$

B. Ultimate case, Effluent discharge rate, $Q_2 = 7.0\ m^3/s$

Hamdy (1981) have computed the following for the above example

$\ell = 6.0\ m$
$x_1 = 10\ m$
$D_1 = 0.20$

Since the nearfield flow is unstable, individual jet plume would merge before reaching the water surface. Therefore, width of the plume at surface equals the diffuser length, b = 210 m (see Figure 3).

In this case, $D_2 = 1.0$
$x_2 = 0$

and the midfield region does not exist.

The computations and results for the farfield and decay are similar to the previous case when $Q = 1.96\ m^3/s$.

therefore:

$$\begin{aligned} x &= x_1 + x_2 + x_3 \\ &= 10 + 0 + 2100 \\ &= 2110\ m \end{aligned}$$

$$\begin{aligned} D_{2110} &= D_1 \cdot D_2 \cdot D_3 \cdot D_4 \\ &= (0.20)(1.0)(0.38)(1.0) \\ &= 0.076 \end{aligned}$$

If the pollutant were a non-conservative, e.g. coliforms. Decay rate for coliforms, $k = 16\text{x}10^{-5}/s$, time to travel a distance of $x = 2110\ m$ is:

$$t = \frac{x}{U} = \frac{211000}{10} = 21100 \text{ s}$$

$$kt = 16\times10^{-5} \times 21100 = 3.376$$

From (13):

$$D_4 = \exp(-3.376) = 0.034$$

For coliforms:

$$D_{2110} = D_1 \cdot D_2 \cdot D_3 \cdot D_4$$

$$= (0.20)(1.0)(0.38)(0.034)$$
$$= 0.0026$$

CONCLUSIONS & RECOMMENDATIONS

The following conclusions can be drawn:

(a) The most important dilution is due to initial mixing and jet rise (D_1)

(b) The dilution due to decay (D_4) of non-conservative pollutants is also significant.

(c) The surface dilutions (D_2 and D_3) of the mid and far fields are very small compared to other dilutions D_1 and D_4.

In order to minimize the areas of the mixing zones, it is important to maximize the dilution (D_1) due to initial mixing and jet rise. D_1 is the only dilution that can be controlled by changes in design for the multiport diffusers. Dilutions D_2, D_3 and D_4 cannot be controlled by any design changes and depend upon natural factors, such as, dispersion and advection characteristics of the site and decay rates of the pollutant.

If no data for currents are available, the dilution computations for average current speeds of 5, 10, and 15 cm/s should be undertaken as representative values. A judicious decision on the appropriate results will then have to be made by the user. Current data should then be obtained as soon as possible to confirm the predictions.

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TABLE 1: Error Function (erf)

x	erf(x)
0.0	0.0
0.1	0.1129
0.2	0.2227
0.3	0.3286
0.4	0.4284
0.5	0.5205
0.6	0.6309
0.7	0.6778
0.8	0.7421
0.9	0.7969
1.0	0.8427
1.2	0.9103
1.4	0.9523
1.6	0.9763
1.8	0.9891
2.0	0.9953
2.5	0.9996
3.0	0.9998
	1.0000

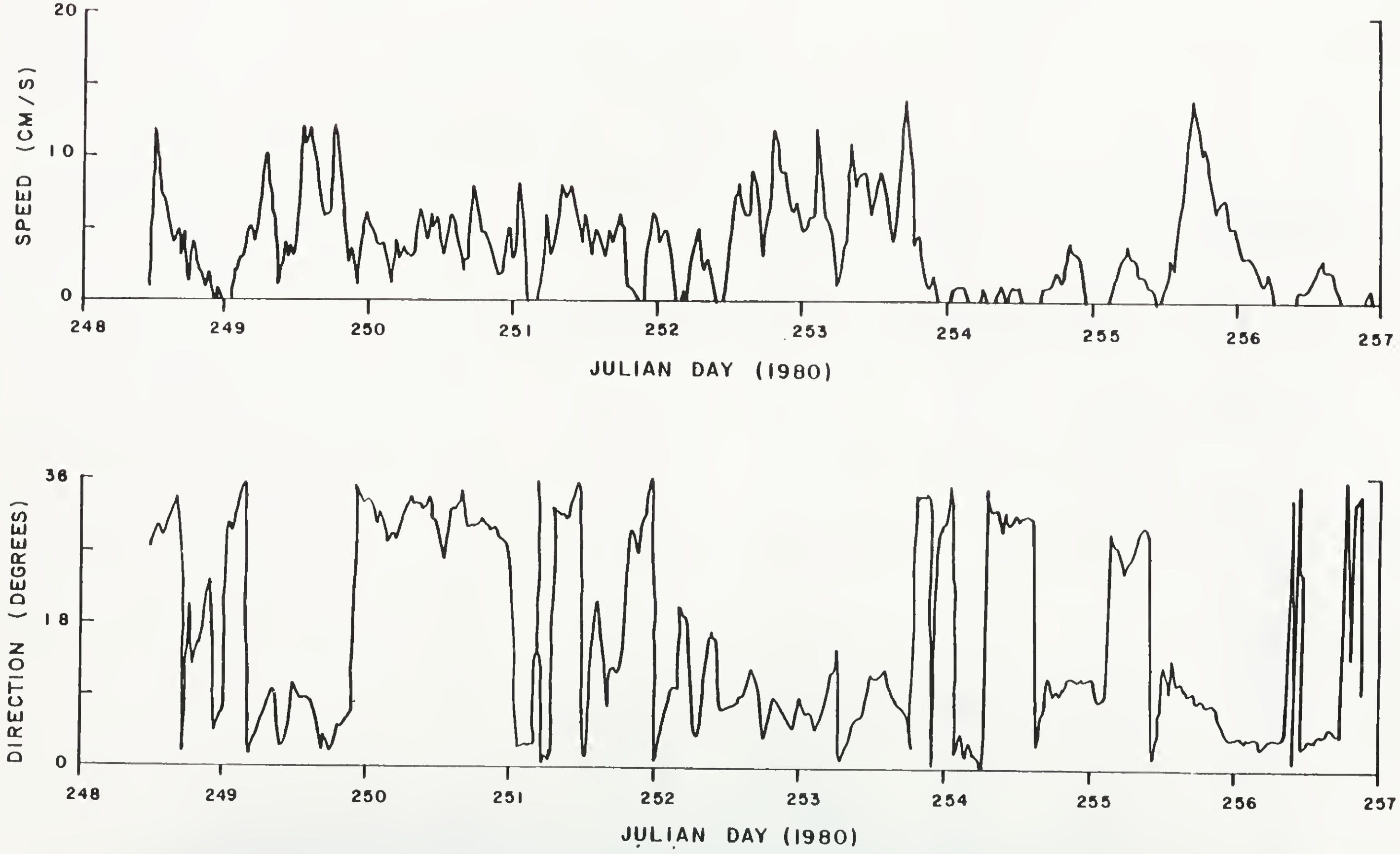

Figure 1 : Variation of Current Speed and Direction With Time (off Duffins Creek, Lake Ontario)

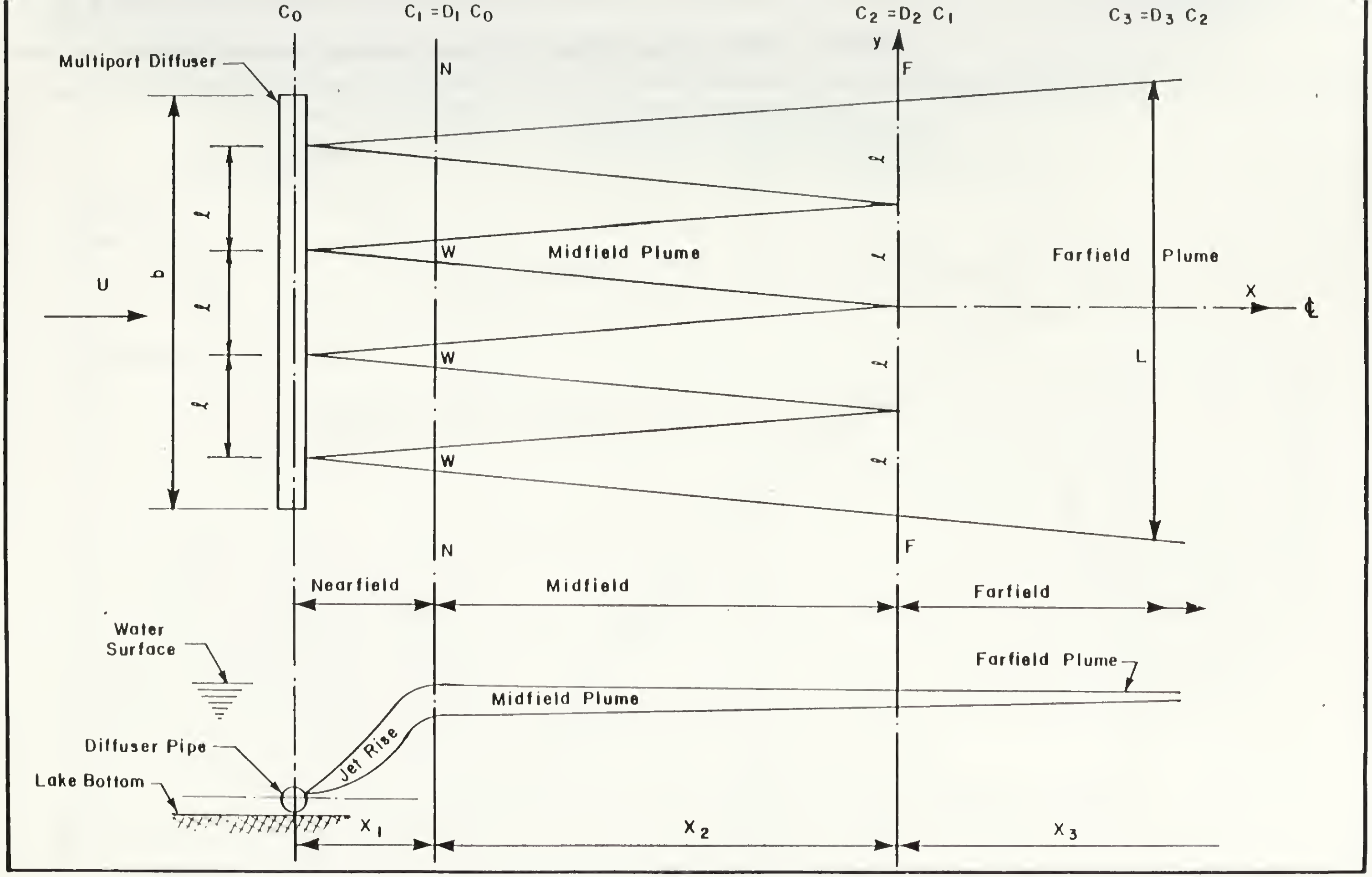

Figure 2 : Schematic Behaviour of Sewage Plume From Multiport Diffuser (Unstable – Nearfield)

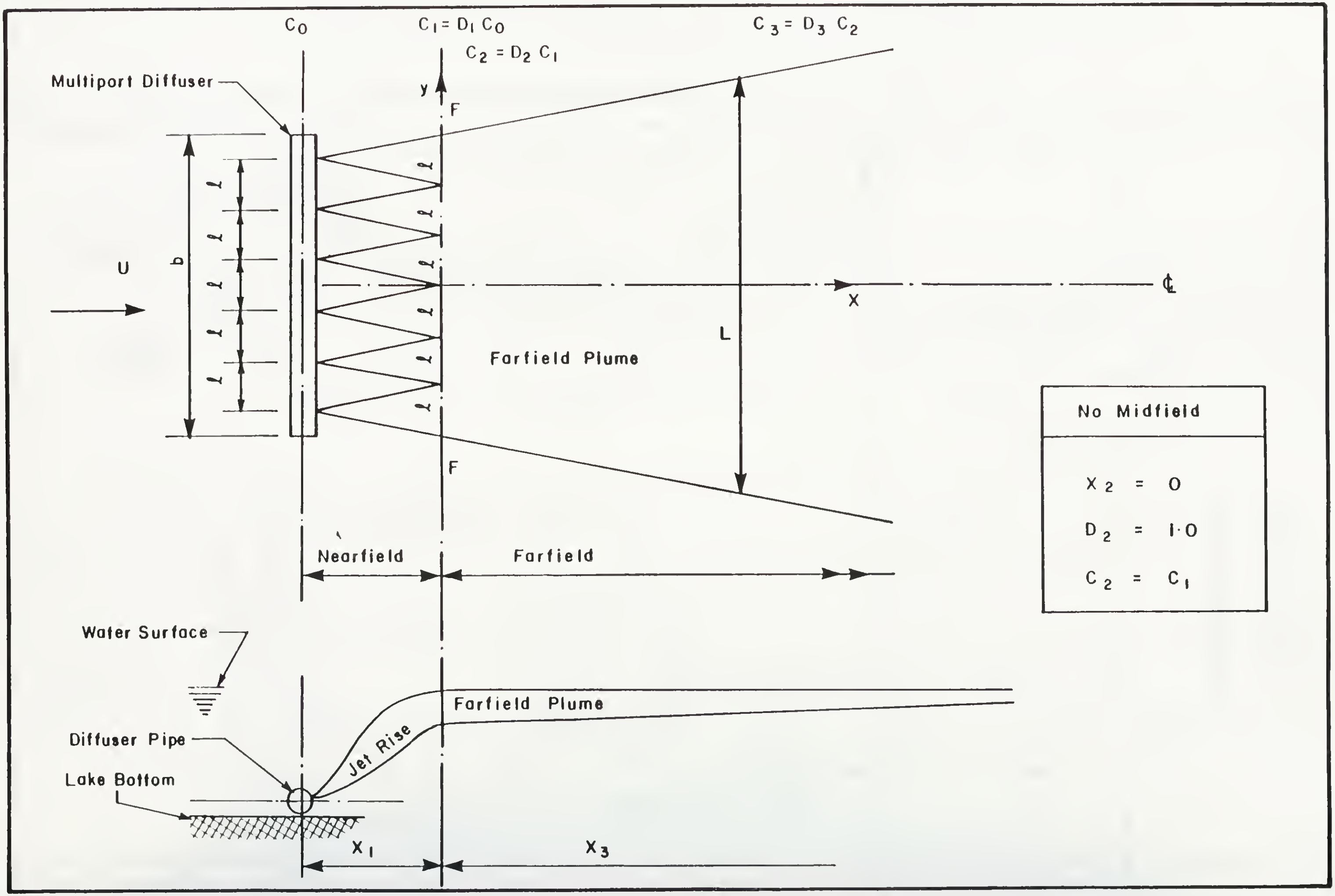

Figure 3 : Schematic Behaviour of Sewage Plume From Multiport Diffuser (Stable – Nearfield)

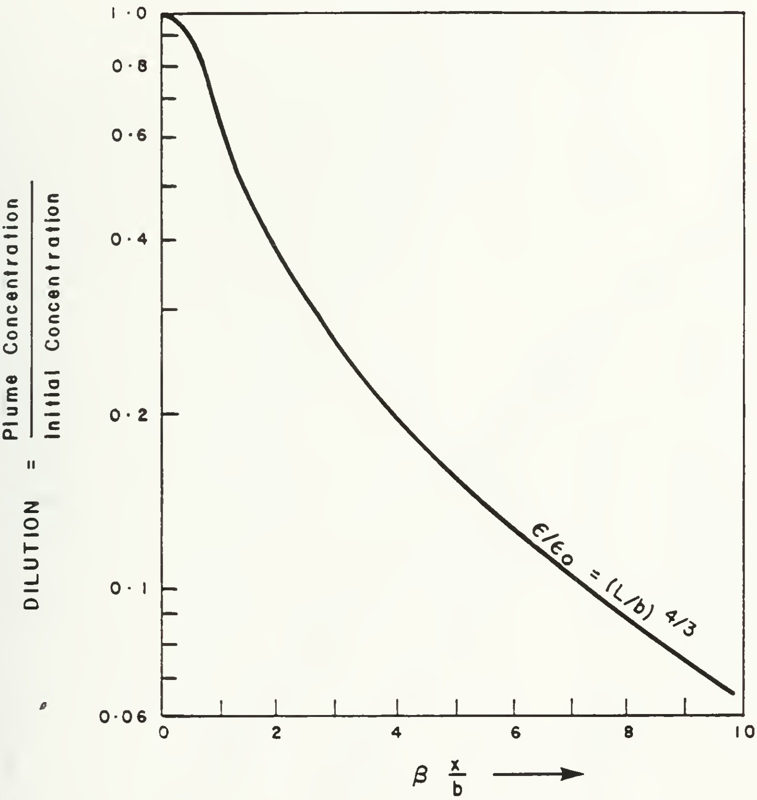

FIGURE 4 : DILUTION ALONG CENTRELINE OF A SEWAGE FIELD (Brooks N.H., 1960)

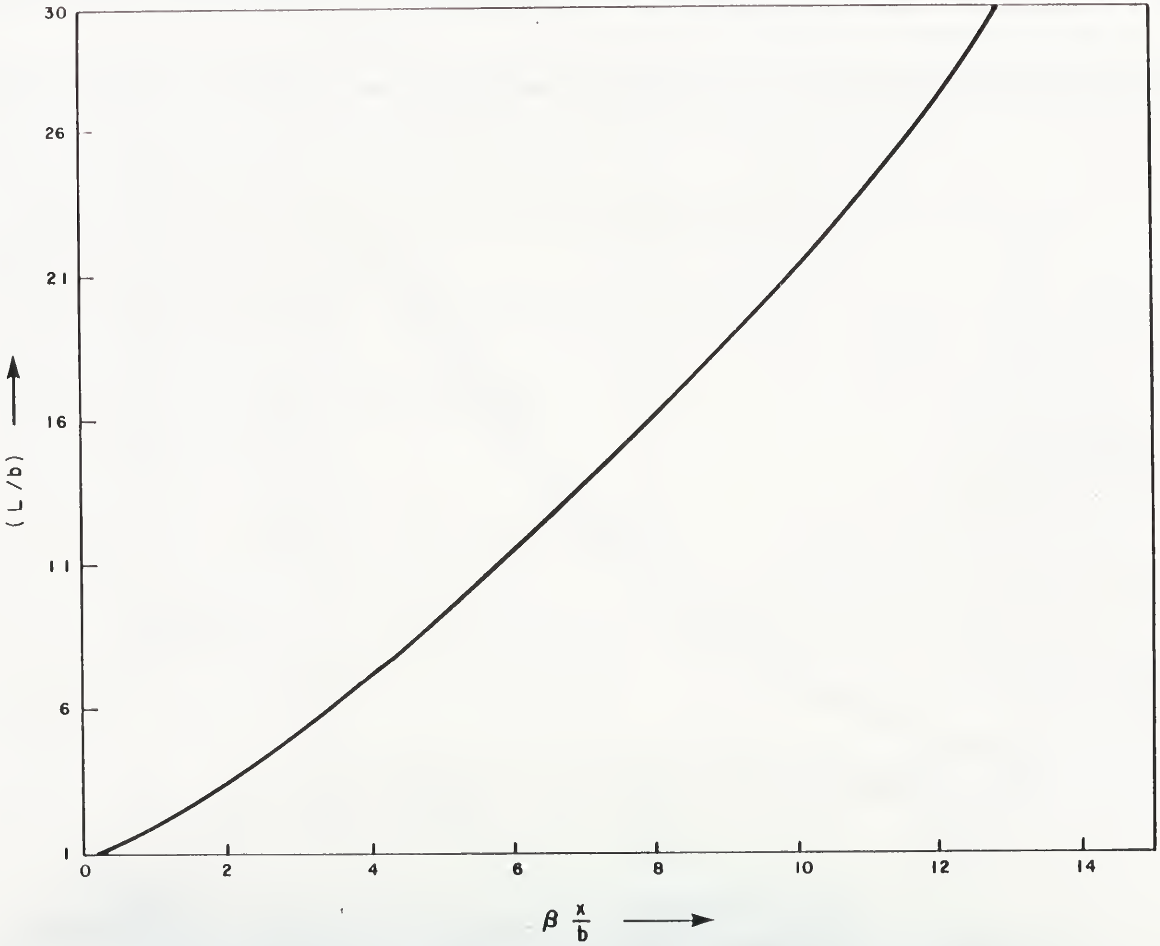

FIGURE 5: WIDTH OF SEWAGE FIELD (L)

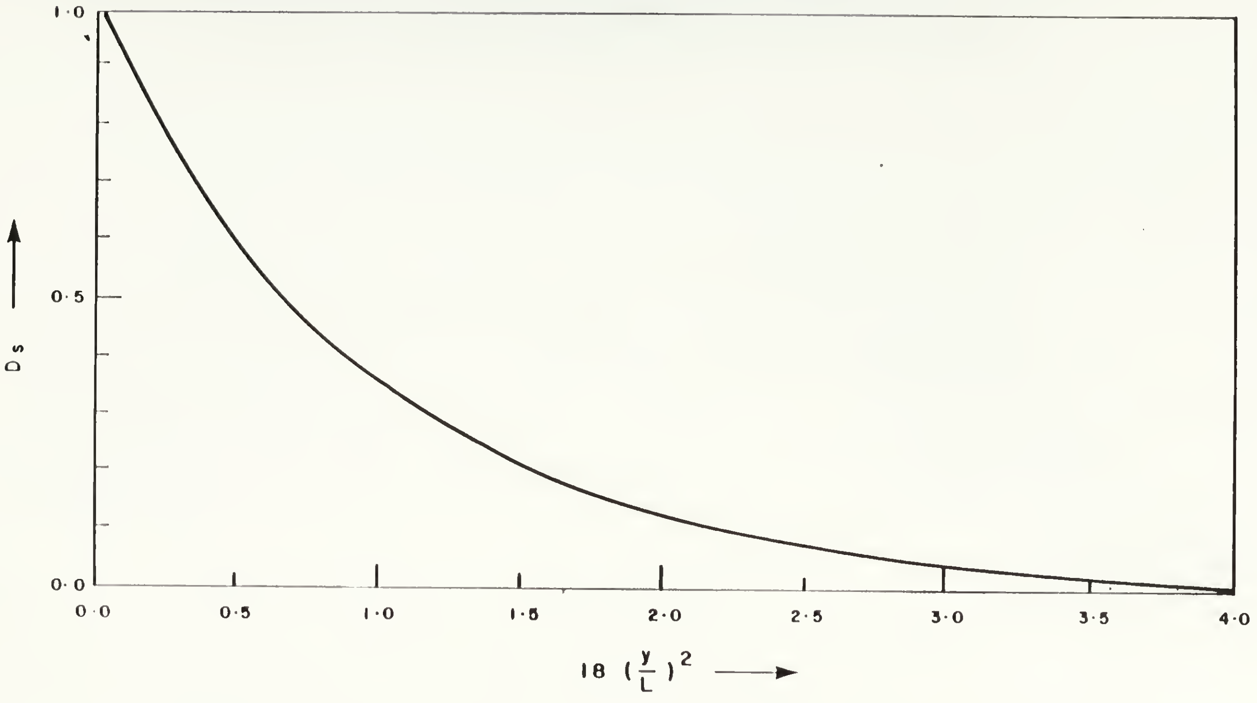

FIGURE 6 : DILUTION ACROSS THE PLUME WIDTH